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REQUIREMENTS AND SELECTION OF LABORATORY ROBOTIC SYSTEMS

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ABSTRACT

This report provides a general overview and outlines a procedure for the design and selection of a laboratory robotic system. The Characteristics and Classification of Robots Section explains the various characteristics and each of the classifications of robot design. The Justification Section deals with the justification for using robotics to automate laboratory procedures. The Design Considerations Section discusses design considerations and system requirements for selecting an automated laboratory robotic system. Finally, the Evaluation of Robotic Systems for Automated Immersion Testing of Materials Section illustrates how selection criteria are utilized to evaluate robotic systems for a particular laboratory application. A detailed example is used to help illustrate the procedure outlined. This example is based on a problem which has already been successfully automated.

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INTRODUCTION

The introduction of robotics technology into the laboratory has proven to be an important tool for the analytical chemist.[1-4] The purpose of this report is to provide a general overview and outline procedures for the design and selection of a laboratory robotic system. The Characteristics and Classification of Robots Section explains the various characteristics and each of the classifications of robot design. The Justification Section deals with the justification for using robotics to automate laboratory procedures. The Design Considerations Section discusses design considerations and system requirements for selecting an automated laboratory robotic system. Finally, the Evaluation of Robotic Systems for Automated Immersion Testing of Materials Section illustrates how selection criteria are utilized to evaluate robotic systems for a particular laboratory application.

CHARACTERISTICS AND CLASSIFICATION OF ROBOTS

The Robotics Institute of America (RIA) defines a robot as follows: "A reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks."[5]

To understand the technology of robotics, it is often useful to define the various technical characteristics around which the robot is constructed and operates. For many of these topics, it may be appropriate to consider them in greater detail. However, the purpose of this section is to provide a general background of knowledge that will allow the reader to understand the considerations necessary for selecting a robotic system.

General Characteristics

To provide a clear understanding of what a robot physically is, it is often helpful to consider a robotic arm to be very much like a human arm; i.e., a series of connected mechanical links or bones that allow the end of the last link (the end-effector, or hand) to be placed at some position and orientation in space. The energy that causes the motion of the arm comes from actuators, or muscles, that drive the motion of each mechanical joint to achieve the desired pose, motion, or force of the end-effector.[6]

Typically, a robotic arm consists of three major subsystems. They are the mechanical linkages that constitute the manipulator and end-effector which includes the actuators that move them, feedback control sensor for measuring the internal state of the robot and determining the environment external to it, and the robotic controller that allows the desired task to be specified and executed.

Manipulator

The physical part of the arm, or manipulator, is described in terms of size, payload or load-carrying capacity, acceleration, speed, resolution, accuracy, repeatability, and the number of degrees of freedom. As with any other complex system, all of these parameters may not be optimized simultaneously.

1. HAWK, G. R., and STRIMAITIS, J. R. *Advances in Laboratory Automation Robotics, 1984.* Zymark Corp., Inc., Hopkinton, MA, 1984.
2. HAWK, G. R., and STRIMAITIS, J. R. *Advances in Laboratory Automation Robotics, 1985.* Zymark Corp., Inc., Hopkinton, MA, v. 2, 1985.
3. HAWK, G. R., and STRIMAITIS, J. R. *Advances in Laboratory Automation Robotics, 1986.* Zymark Corp., Inc., Hopkinton, MA, v. 3, 1987.
4. HAWK, G. R., and STRIMAITIS, J. R. *Advances in Laboratory Automation Robotics, 1987.* Zymark Corp., Inc., Hopkinton, MA, v. 4, 1988.
5. GROOVER, M. P. *Industrial Robotics Technology Programming and Applications.* McGraw-Hill, Inc., NY, 1986.
6. SCOTT, H., and STROUSE, K. *Workstation Control in a Computer Integrated Manufacturing System.* Proceedings of Autofact 6, October 1984.

Size and Payload: Payload may be defined as the maximum amount of weight a robot can move from one point to another while operating within the prescribed specifications for the system. Some manufacturers consider the end-effector (hand) to be a separate system, rather than a part of the manipulator (robotic arm). This means that the specification given by the manufacturer for payload usually does not include the end-effector weight. In fact, payload is usually considered as a gross estimating factor when selecting a robotic manipulator.

A slightly more accurate evaluation criterion for payload is inertia. A robot may have a given payload specification, but it is important to know under what conditions this payload may be handled safely. Some manufacturers specify a payload rating at full extension of the manipulator and at maximum speed. Other manufacturers list a maximum payload without giving any relationship to speed or arm position. They may be giving a maximum payload that can only be reached with a restricted arm position and a dramatically reduced speed.

The payload's center of gravity relative to the robot's end-of-arm mounting plate is also an important consideration. Most robotic payload capacities are given for a load placed directly on the mounting plate. However, if an additional axis of motion is added between the mounting plate and the end-effector, such as roll, pitch, or yaw, the extended distance between the mounting plate and the end-effector, or end-of-arm tooling, will reduce the payload capacity. This is primarily found in robots whose manufacturers provide optional axes of motion to be located at the end of the robot arm. The specific information regarding the effect of these options may be obtained from the manufacturer.

Acceleration, Stability, and Speed of Response: Acceleration is a primary function of the power that can be developed by the driving forces of the robotic arm. For short motions, i.e., as in pick and place operations, acceleration is one of the dominant factors in determining the cycle time. For all configurations, speed of response and the lifting capability, or generative load torque, of the robot are related in a complex way to the lifetime and reliability of the robotic manipulator and end-effector. Speed of response refers to the time required for the robot to move to a new location. This response time is not only related to the robotic actuators (muscles), but also to the robotic control system as well.

A good indicator of the overall speed of a robot is given by its typical instruction execution speed. This is defined as the overall average time required for the system to interpret and execute one user-defined command. Hence, this time would be a function of both the microprocessor and operating system speed, as well as the response time for the robot. The typical execution speed of each robotic system is specified by the manufacturer and, may, therefore, be used as an evaluation criteria.

In certain areas of operation, a robot may experience unbounded or uncontrolled behavior. This type of behavior is known as instability. Instability results from the complex relationship between speed, acceleration, and generative load torque inside the robot controller. The control system should be designed to avoid these areas of operation without adversely affecting the flexibility of the system.[7] The stability of the robot is generally defined as the measure of oscillations which occur in the robotic arm as it moves from one location to another. A highly stable robot will exhibit very little, if any, oscillation during or after completion of the movement, while a robot with poor stability would be characterized by a high degree of oscillation. It is generally desirable for the robot to have both high stability and a

7. CRAIG, J. J. *Introduction to Robotics Mechanics and Control.* Addison-Wesley Publishing Company, MA. 1986.

quick response time, but since these are mutually exclusive goals, some form of compromise must be made. The reason for this compromise is that, to a large extent, a robot's stability is controlled by the dampening elements incorporated into its design. A high degree of dampening will decrease the robot's tendency to oscillate but, will, at the same time, prevent the robot from having a quick response time.

Resolution, Repeatability, and Accuracy: Resolution, sometimes referred to as precision, is the smallest step size or increment of motion that the robot can perform. The minimum step size is mandated, in this case, by the tasks required of the system. Repeatability, or the robots ability to return to a previously specified point in space, measures the stability of the robots internal coordinate system. Accuracy is used to measure how well the robot can conform to an ideal world coordinate system.

Repeatability, accuracy, and overall performance are primarily a function of the quality of the components used in the system design. These components include encoders, bearings, servo and stepper motor quality, and gearing. Repeatability is also a function of load and temperature changes. For most applications, these quantities are considered as constants which are specified by the manufacturer and, may, therefore, be compared on an individual basis.

Degrees of Freedom: Six geometric parameters are required to completely specify the location and orientation of a rigid object within some coordinate system. Three coordinates locate the object's center of gravity. Three angles are then used to specify the object's orientation around its center of gravity. Complete general manipulation of an object, therefore, requires a robot arm to have at least six controlled axes or degrees of freedom. For the most part, these axes are then mapped into three large-scale translational axes, such as the cartesian coordinate system.[8]

Very often, a robotic arm does not need to be oriented to all parts of its environment and, hence, fewer degrees of freedom may be used. In order to orient an object in a plane, three degrees of freedom will be required; i.e., x, y, and θ. An additional motion, normal or perpendicular to the plane (known as the z axis in the Cartesian system), will allow approach to and from the plane. These motions are achieved through the use of a fully articulated robotic design. Here, a wrist and end-effector could provide the radial degree of freedom, while the manipulator provides the three axes of motion. This design will deliver four of the six degrees of freedom possible and, therefore, will directly duplicate most manual tasks. It can be shown that this is the minimum required number of degrees of freedom necessary for a laboratory robot to complete most of the required tasks.

Feedback Control

Feedback is the process where part of the robot design includes a system to indicate the current position of each of its moving parts or axes. When the controlling system continuously monitors the position of each of the moving axes, and can make fine adjustments in position to achieve the desired target position, the system is said to be servo controlled.

Most of the currently available laboratory robotic systems include some type of servo control feedback. There are a large variety of commercial devices available for sensing position. The three most common are potentiometers, resolvers, and encoders.

8. L'HOTE, F., KAUFFMANN, J. M., ANDRE, P., and TAILLARD, J. P. *Robot Technology Robot Components and Systems.* Prentice Hall, Inc., NJ, v. 4, 1981.

Potentiometers: A potentiometer is an analog device whose output voltage is proportional to the position of a rotating wiper. This rotating wiper provides an electrical connection to a resistive element. As the wiper is rotated about, more or less of the resistive element is added to the circuit, causing a variation in the output voltage proportional to the position of the wiper. This method is usually used since it provides the simplest and least expensive type of feedback.

Resolvers: This is an analog device whose output is proportional to the angle of a rotating element with respect to a fixed element. A resolver may be thought of as a rotating transformer. If an alternating voltage is applied to the rotating coil portion of the resolver, a different voltage proportional to the angle of rotation will appear on the stationary portion of the resolver. The important thing to remember here is that resolvers are designed to work only with an alternate current (AC) voltage. If a direct current (DC) voltage were applied, the output of the resolver would be null.

Encoders: As computer control becomes common in robotic design, the use of digital position sensors increases. Encoders are available in two types; incremental and absolute. There are many different designs of incremental and absolute encoders. The most popular is the optical shaft angle encoder. This design consists of a glass disk that is marked with alternating transparent and opaque strips which are radially aligned. On one side of the disk is a light source, while on the other side there is a light sensor. As the disk is rotated, the light beam is pulsed or broken. The output of the photoreceiver (light sensor) is a series of pulses where the frequency is proportional to the speed of the rotating disk. This type of optical encoder is called an incremental encoder.

The problem arising here is since incremental encoders do not have an inherent zero reference point, it is necessary to establish a zero, or home, location for each joint. This requires the operator to initialize the robot to a known location prior to the running of each user-defined program.

To solve this problem, it is desirable for the robot to know the exact, or absolute, position of each of its axes. For this reason, absolute optical encoders are used. This type of encoder uses the same basic construction as the incremental encoder except that there are additional tracks of strips with corresponding photoreceivers and phototransmitters (light sources) added. These strips are then arranged to provide a binary code for the angle of the encoder shaft. This information may be uncoded by the robot controller, and used to determine the starting position for each axis.

Other Control Devices: Some robotic designs include other types of feedback control. Such sensors include tachometers and limit switches. A tachometer is essentially a DC generator providing an output voltage proportional to the angular velocity of the armature. Tachometers are used to feedback information on the velocity of the moving axis. They may also be used to increase the dampening coefficient of the control system, thereby improving robotic stability and its response to disturbances.

Limit switches are used primarily to detect the presence or absence of an object. A limit switch, or touch sensor, is an electrical on/off switch that is mechanically activated by depressing a button or lever. If the object that is to be detected is a physical stop placed at a desired target position, the sensor may then be used to send a feedback signal to the controlling system. This signal would be used to identify that the target position had been reached.

Robot Controller

A robot controller is used to generate the particular control signals that coordinate the motion of the joints and linkages of the manipulator and end-effector. There are two types of control signals that the controller may generate. The first is "low-level" control. These are the signals used to drive the basic physical movements of the robot. The second type of control is "high-level" control. This is where the more advanced control signals for planning and monitoring the overall tasks are generated; an example would be the raising of the end-effector (hand). This operation may be achieved by "shoulder" motion, "elbow" motion, or both. This type of basic motor control is represented as low-level control, while high-level control is needed for calculating the overall path that the robot will take and monitoring its progress to see that it reaches its destination.

It is, therefore, the high-level control that dictates to the low-level control the pose of the arm and end-effector. It is also the responsibility of the high-level control to tell the end-effector "what to do when it gets there." The overall goal of the computer is to determine the particular sequence of link motions and end-effector operations that will accomplish the given task, and then drive the manipulator and end-effector to achieve the desired motions and operations.

While the robot arm may provide the muscle to carry out the tasks necessary to complete the job, it is the computer program that directs the arm and provides the "intelligence" that makes the robot successful. The easier the robot is to program, the more closely the programming language must reflect the desired tasks that the user wishes to accomplish. The structure of most robotic languages resembles that of many computer languages. This should not be a surprise since the people developing most of the robotic languages are computer programmers. In addition, many of the tasks required to be automated can be analyzed by the same logical structure used to develop computer programs.

Programming Features: The following programming language features are typical of the ones found in a majority of the commercial robotics systems that are presently available.

1. Home. The programming concept of home is universal among robots. This is the way of defining the beginning, or reference point, for the robot. All calculations and moves are recorded and calculated with respect to this point. Home is defined for all axes so that each axis may return to its original position. In some machines, home is hardware as well as software defined. This may be accomplished by microswitches that may be activated when key positions are reached. Other machines allow the user to redefine the key home positions via software or computer control.

2. Main Line. The logical flow of the major tasks of the program is called the main line of the program. Once the main line program is developed, subroutines may be added to perform additional tasks from within the control of the main line program.

3. Subroutines. Subroutines are smaller than the main line program and are a subset of the main program. Two different approaches are common in the use of subroutines. The first approach incorporates most of the program into the main line program, and then calls on subroutines to modify or add functions to the main program. The second approach involves creating several subroutines, and then having the main line program be made up primarily of these subroutines used in a variety of sequences. In both cases, the subroutines or

branches can be executed on either an always or conditional basis. The conditions for branching (or not branching) can be defined by software such as with flags or counters, or they can be externally defined by hardware signals.

In its simplest form, a robotic program may be defined as a series of instructions which direct the manipulator through a series of predetermined movements. This program may be expanded to include the control of the end-effector and transfer of signals to and from the various sensors that may be located on the robot. One of the primary reasons that robotics offers such great flexibility is the ability to edit the robotic control program and teach the robot new routines easily and effectively. The three methods most commonly used for programming and teaching a robotics system are listed in the following paragraphs.

Teach Pendant Method: The teach pendant method allows the user to manually direct each axis to a desired position. It consists of a hand-held keypad device with some type of display. The display is used to provide operator prompts, position data, and error messages. The five major functions that can be performed in the teach mode with the pendant are:

1. Command any axis to move to a new position,

2. Jog any axis, either forward or backward, in small increments,

3. Record the present position of any axis and store in RAM (controller memory),

4. Store a completed series of moves to some form of mass storage (tape, floppy disk, hard disk, etc.), and

5. Edit a series of moves in the controller memory.

After the desired series of moves has been recorded, the robot may then be instructed to step through them.

Off-Line Programming: The second method for programming a robotic system is through the use of off-line programming. Here, the user writes the necessary motion control program on the host computer system. This is done much the same way as he or she would write any other computer program. The finished code is then downloaded to the robot controller. As a precaution, the user then executes the program at a greatly reduced speed, single stepping through if possible, to make sure the code is correct before operating the system at normal speed.

On-Line or Remote Programming: The final method called on-line, or remote, programming is a method by which the user can write a generic motion control program, and then upload a specific set of position coordinates from the robotic controller to the main program. This is accomplished when the user begins writing the main motion control program, and when the coordinates of a specific point are desired, the on-line option is selected. Now the user is free to position the robot to the desired location with the teach pendant. When complete, the coordinates of the new location can be uploaded into the main program. The procedure is then repeated until the program is complete.

These programming methods are standard on most commercial robotic systems. Other features of interest include:

1. Variable velocity programming,
2. Variable force programming,
3. Automatic execution of user-defined programs on system start up,
4. Diagnostic software for trouble shooting a defective system, and
5. Simultaneous execution of multiple programs.

Robotic Classifications

Robotic systems are classified by three basic parameters of design: (1) The first is in terms of the actuator drive mechanism. This is the means by which power is provided to the robot allowing it to carry out the prescribed tasks. (2) The second parameter is the type of control mechanism that is used by the robot to maintain the required specifications for accuracy, precision, etc. (3) The third descriptive parameter is the robotic workspace. This is used to define the reach, or work, envelope that the robot is capable of performing in.

Power Supply

The primary methods used to power robots are hydraulics, pneumatics, and electrical. Pneumatics and hydraulics operate on essentially the same principles. The primary difference between the two systems is that in the case of hydraulics, the fluid is noncompressible, while in pneumatics the air is. This provides for much larger payloads to be handled by hydraulic systems. Pneumatics are primarily used in the simpler pick-and-place robots for carrying lighter payloads. Pneumatics may also be used in the end-effector or end-of-arm tooling to grasp a part, either through the inflation of a bladder, or the pulling of a vacuum.

Many people believe that the future of robotics is in the use of electric systems. This is due in part to their advantages over hydraulic systems; for example, there is not the required warm up time for electric robots as there is for hydraulics. Electric robots do not require a separate power supply as do hydraulics with their associated hydraulic pumps. This allows for electric robots to consume less energy, since they only require power when their axes are in motion. Hydraulic robots, on the other hand, require that the hydraulic pumps be in operation continuously, even if the robot is not in motion.

Hydraulic: The basic hydraulic system consists of a fluid tank, pump, surge tank, lines, control valves, and actuators. Hydraulic fluid is transferred from the fluid tank through the various lines by the pump. The control of this fluid flow is handled by several different types of control valves. The control lines lead to each of the hydraulic actuators, which provide each of the different robotic capabilities. It is important to realize the dangerous pressures that are often involved in the driving portions of a hydraulic system. Pressures of several thousand pounds per square inch are common in larger robotic systems. At this pressure, a pinhole leak in a fluid line could cause severe physical damage to an unaware operator or observer. For a given size actuator, a hydraulic robot can generate a higher torque and, therefore, carry a greater payload than an electric robot. The hydraulic robot is usually less expensive for comparable capability.

The hydraulic systems associated with robotics will commonly use a surge tank in the high pressure side of the line. This tank is used to provide the high volume of hydraulic fluid

needed when rapid motion is required. Since this increased demand could not be met by the hydraulic pump alone, the surge tank provides intermediate storage for the high pressure fluid.

Another important point to realize about hydraulic systems is the requirement for stringent filtering of the hydraulic fluid. Very small contaminants in the hydraulic fluid can cause the system to wear out very quickly. Therefore, a filtering system capable of removing particles down to a few microns in size is an essential component for the robotic system. A comprehensive maintenance schedule for changing and repairing the filtering system should also be included. An additional consideration is that hydraulic systems will typically leak (fluid) to some extent. This may prove to be a hazard in a clean environment.

Pneumatic: Pneumatic systems are designed to use the same types of valves, pumps, and actuators as those used in hydraulic systems. In addition, pneumatic robots may contain such devices as amplifiers and logic control systems that are very similar to those associated with electronic robotic systems. Most laboratory facilities have compressed air available, so there is a great temptation to develop low cost, high technology robots that would not need the added expense of hydraulic pumps and lines to operate. It is unfortunate that these techniques have not as yet provided a notably successful system. The only major maintenance problem associated with pneumatic systems is the need for clean air. Like hydraulics, a filtering system is required to keep the air clean and dry.

Electric: Electric motors provide one of the most universal methods for converting from one type of energy source to another. Although any type of electric motor may be controlled by a computer, DC motors are the most common type used in robotics. The primary advantages of electric robots over hydraulic robots are the DC servomotors of an electric system are unlikely to be contaminated or damaged during regular maintenance, while in hydraulic systems, contaminants often get into the hydraulic fluids during maintenance and repair, causing the ultimate breakdown and failure of the servo control valves. Electric systems are generally more accurate in their operation, while running smoother and quieter than their hydraulic counterparts.

All electric motors are electromechanical devices which convert electrical energy into some type of mechanical rotation or movement. The two major characteristics of DC motors are: (1) They are reversible. If the polarity of the applied power is reversed, the direction of rotation is also reversed, and (2) the speed of rotation is variable. By varying the applied voltage, the speed of rotation is changed. This variation in voltage will also affect the amount of load that can be supported. The variation in load torque is dependent on the motor design and construction.

There are two major types of DC motors used in robotics today; the regular DC motor and the DC stepper motor. AC motors are primarily used to power the hydraulic and pneumatic systems (operation of pumps and compressors). These motors are usually run continuously so there is not a need for motor control. The regular DC motor is used as the power source for most laboratory robotic systems.

Stepper motors, although different in construction, can be used to perform the same function as regular DC motors. The advantage is that stepper motors can easily be driven in incremental degrees of rotation. This provides for precise computer control, allowing the robot to be accurately positioned without an elaborated feedback control system. Stepper

motors are commonly used in educational robotic systems, and are slowly becoming popular in other areas of robotics.

Control Mechanism

Robotic control may be characterized as either a point-to-point, or a continuous path system. Point-to-point systems are available with either servo or nonservo control, whereas continuous path systems are usually always servo controlled.

Point-to-point: Point-to-point control refers to the robots ability to traverse a path that is made up of a series of individual points. The robot must be taught each of these individual points, which are then recorded in the robot controller's memory. During program execution, each point is recalled from memory, and the robot is sent to each of these locations in the proper sequence. Point-to-point robots do not provide any control over the path that is used to reach each of the defined points. Therefore, if the programmer wishes to specify a specific path of travel from one point to the next, he or she must specify additional points along the desired path of travel. This will allow some control over the path followed by the robot, and should prove to be adequate for most operations.

Continuous Path: Continuous path robots are used to perform operations where the path of travel must be controlled. This is usually accomplished by allowing the robot to move through a series of very closely spaced points which describe the desired path. The important difference is that unlike the point-to-point system, the continuous path controller determines the points, not the programmer. Since this type of operation would require the robot controller to be able to store a large number of positions, most systems use a digital computer as the robot controller. Typically, such systems are used for the spraying of coatings or paints where accuracy is not critical, but the path is.

Servo Control: A servo, or servomechanism, is a device used to determine the exact position of a moving object at any time. This is accomplished through the use of feedback devices, such as those mentioned earlier. In the case of a servo controlled point-to-point robot, the controlling computer checks the location of all the moving parts of the robot and can make small adjustments in their position as required. Each position is compared with the target position to see if the difference is zero. When the difference is zero, the target position has been reached. For continuous path robots, this type of control is usually built into the system design.

Nonservo Control: A nonservo-controlled point-to-point robot is one in which the robot is told by the controlling computer to move to a position. It then must assume that the robot will reach the target position. Any difference between the robot's actual position and the target position is reflected as an error. This type of error will have an adverse affect on the repeatability of the robot.

At first, it seems that a nonservo robot could not function in a laboratory environment. Two techniques have been developed that allow this type of robot to function adequately for specific applications. The first method gives a type of feedback that is not continuous, but is highly accurate. This method involves placing physical stops, or switches, where a movement is to end. With this system, the robot will not make the second move until the switch indicating the completion of the first move have been activated.

The second method is to use a very reliable drive system that will always move as directed. The electric "stepper" motor is used for this application. This motor will only rotate the precise number of degrees that it is told to move. Therefore, the control computer can direct the stepper motor to rotate a fixed number of degrees, and the task has a high probability of being completed. The only disadvantage of this procedure is that if the stepper motor is overloaded or stalled, it may slip. If this occurs, then the error created results in all subsequent rotations being out of place.

Nonservo-controlled robots are used where a limited number of motions are needed (typically three or four axes). Here, high speed and a high degree of accuracy (if the load is properly controlled) may be achieved. Pick and place operations, where a large number of difficult steps are not required, are good applications for this technology. For complex tasks requiring a large number of movements with ease in programming, and the cost of a faster control computer is justified, a servo-controlled robot is recommended.

Work Envelope

Workspace, or work envelope, are terms used to define the area within which the robot performs its function. The transversable path of the robot's wrist has been adopted as the conventional method of describing the work space. The reason for this is that the end-effector is additional to the basic robot. Since various size end-effectors are usually available, this would affect the defined values for the work envelope.

The following four coordinate systems provide the basis for most robotic designs: (1) Cartesian or rectangular, (2) cylindrical, (3) polar, and (4) revolute or spherical system.[9]

The Cartesian Coordinate System: The Cartesian coordinate system involves linear movement on each of the three or more axes. As a result, the workspace for such a robot is divided into planes of movement causing the system to appear in a gantry, or box, configuration. This coordinate system is mainly used in applications where there is a high demand for horizontal travel. Some examples would include assembly tasks (such as plugging in modules on a printed circuit card), and stacking or palletizing parts in bins.

The Cylindrical Coordinate System: The cylindrical coordinate system is created by changing the y axis of the Cartesian system from a linear motion to an angular, or rotational, axis. Many laboratory robotics systems are designed in this fashion. In this case, the vertical axis rotates about a fixed base. The horizontal axis is then left free to move up and down along the vertical axis, and can be extended or retracted. This configuration provides for three degrees of freedom from the manipulator, with an additional degree of freedom being provided by the wrist and gripper.

Polar or Jointed Spherical Coordinate System: Changing the horizontal arm from a linear action to a rotating action on the cylindrical configuration creates what is known as the polar, or jointed, spherical coordinate system. The primary advantages of this configuration are simplicity of design and increased lifting capability. The primary application for this design involves tasks where a small amount of vertical motion is required. A typical example of such an application would be in the loading and unloading of instruments, equipment, or part racks.

9. HEATH, L. *Fundamentals of Robotics Theory and Application.* Reston Publishing Company, Inc., NJ, 1985.

Revolute or Spherical Coordinate System: Rotating the base, shoulder, and elbow axes about their centers creates what is called the revolute, or spherical, coordinate system. This is by far the most versatile system since it gives the largest workspace. The disadvantage is in the increased difficulty in programming. Since the programming for this structure is tedious and requires the transformation of all points to three radial axes, this system is only used with robots having high-level computer control.

Laboratory Robotics

While it is true that industrial robots have been around for about 25 years now, the manufacture of laboratory robotics is relatively new, having only been available for 7 to 8 years. While it is also true that a small industrial robot may be configured to run in a laboratory environment, it is possible that such a system may be both more expensive and more difficult to set up. The main reason for this difficulty is that a laboratory robotic manufacturer is dedicated to designing equipment for a laboratory environment. Most of the necessary laboratory peripheral equipment has already been designed and is available with the robot as a complete system. If one were to look toward an industrial manufacturer as a potential source, it is possible that some, or all, of the equipment would have to be custom designed for the application. This can prove to be a costly and difficult to maintain solution.

Typically, laboratory robots are used to carry out a variety of different tasks. Such tasks may include the movement of samples and glassware from one point to another, the introduction of samples into automated test equipment, the mixing of liquids, the dispensing of various reagents, and the weighing of samples.

For the most part, the laboratory robots that are used to carry out these tasks have the following basic structure: They are usually tabletop robots with approximately a 12-inch-square base or footprint. They may be anchored to the work table, or suspended above it. They may weigh between 25 and 40 pounds. Their cost ranges anywhere from $10,000 on up, with an average cost of $25,000. Most of the systems will deliver four of the six possible degrees of freedom and use point-to-point servo control with potentiometric feedback. The systems are usually electrically driven with DC servomotors providing the means of movement. There is usually a separate unit that functions as the robot controller, which may or may not include a microcomputer (usually a PC) for additional control.

Since most of the objects that the laboratory robot will be working with are small, their payload range is from three to five pounds. Since this type of application requires a high degree of dexterity, laboratory robots usually exhibit a very good repeatability from 4/100 to 4/1000 of an inch, depending upon the user's requirements. Laboratory robots are also programmable down to very small incremental movements. This ability gives them a precision, or resolution, of between 1/100 and 4/1000 of an inch, also depending on user need. The velocity of a laboratory robot is relatively slow as compared to that of an industrial system. The typical system is designed to operate safely with a maximum velocity of around 20 inches/second.

Programming of the laboratory robot is normally accomplished through the robot controller. All of the methods of programming mentioned earlier are usually provided for with the teach pendant listed as an option. The programming work envelope, or work space, is usually constructed around either a cylindrical, or jointed, spherical coordinate system.

In a laboratory environment, the robot is typically surrounded by peripheral equipment. This equipment is then used by the robot to help fulfill its tasks. Such equipment may include automated balances, automated testing equipment (such as an automated mechanical tester or an automated titration station), liquid or solid dispensing apparatus, and automated mixing devices. Sometimes racks are used to hold the various samples and containers that are waiting to be processed. Some type of mechanical device for the removal and replacement of caps on laboratory jars is also commonly used.

JUSTIFICATION

Should You Automate?

Justification of a laboratory robotic system can be a difficult and time-consuming process, but like any other good investment, the time spent evaluating all of the available options will pay off in the long run. One should also remember to consider the cost of site preparation, and the cost of any peripheral equipment that may be needed to get the system up and running. Thousands of dollars are spent each year for advanced robotic systems that are never utilized to their full potential. For these systems, the tasks might have been equally handled by fixed automation, or by less advanced (and less expensive) robotic systems.

In some cases, the task may not be appropriate for automated techniques. Any steps that require the use of two hands, for example, may provide a challenge for a single robot design. Applications that require a judgement call on the part of the technician may cause problems in automating the technique. The designer should not be discouraged by these less than ideal methods. Often alternate procedures exist which may be more easily adapted to automation. Even if the present method appears to be feasible, it is still a good idea to look at each step carefully and consider if one of the alternate methods may be superior.

Factors to Consider

Besides the obvious benefit of the cost savings associated with direct labor and increased output, laboratory robotics offers other benefits that are equally important. Some of these include better processing quality, elimination of undesirable tasks, improved safety through the elimination of hazardous jobs, flexibility, and increased productivity.

Quality Improvement

The introduction of robotics into the laboratory environment can produce improvements in the quality, reliability, accuracy, and the precision of experimental results. This is justified by the fact that a laboratory robot is capable of performing a series of tasks repeatedly with the same accuracy and reliability each time the task is performed. The increase in quality comes about as a result of having an established procedure for sample processing which is consistently followed. This well-defined procedure sets a reproducible standard for obtaining the experimental results.

Elimination of Undesirable Tasks

Laboratory robotics may be used to handle those tasks which may be considered unpleasant for a human operator to undertake. Such tasks may include the implementation of techniques that are routine or monotonous, and involve activities that are tedious or may cause

physical discomfort. Tasks which must be carried out over long periods of time, such as environmental aging studies, may also prove to be ideally suited for laboratory automation.

Safety

Improved safety for laboratory technicians may result when robots are used to implement those techniques which involve the use of hazardous chemicals or equipment.

Flexibility

By implementing robotic systems rather than fixed automation into the laboratory, the user has a greater degree of flexibility in modifying or improving the system as time goes on. As more efficient methods of testing are developed, the robot may be adapted or reprogrammed to work with new equipment, or implement a new experimental method. In the case of fixed automation, this may or may not be easily accomplished.

Increased Productivity

The increased productivity results more from the consistent pace of the robot than from any speed advantage that the robot may have over a human operator. There is also the possibility that the robot may run a continuous 24-hour schedule. This would require only a minimal shut-down period for maintenance and repair. The end result would be more tasks being completed per day than if a human operator were involved.

Economic Factors

In addition to the technological aspects of automating certain tasks in the laboratory, there are also economic points that should be considered. *Is the robot economically justifiable for this application?* In most companies, it is the economic analysis that determines whether or nor the project is approved. Such an analysis usually consists of the following general information:

1. The type of project being considered; this is usually a description of the intended function of the robot,

2. The cost of the installed robotic system,

3. The time and manpower required to perform this function manually, and

4. The expected savings and benefits resulting from the automation of this function.

The next step is to study the direct costs associated with the robotic system. These costs are usually divided into two types: (1) investment costs and (2) operating costs. These costs may be further broken down as indicated in the following paragraphs.

Investment costs

1. Robot Purchase Cost: The basic price of the robot from the manufacturer equipped with the proper options (excluding end-effector) to perform the function.

2. Engineering Costs: The cost of planning and design by either the user or the manufacturer to install the equipment.

3. Installation Costs: This includes the labor and materials needed to prepare the installation site, as well as any cost incurred as a result of having a manufacturer's representative present during installation.

4. Special Tooling: This includes the costs associated with the end-effector, position sensors, and any support equipment that may be required.

5. Training: This cost may be considered as an investment cost since most of the required training will occur at the time of installation, but training may also be considered as a continuing activity, and could, therefore, be included as an operating cost.

6. Miscellaneous Costs: This covers all additional investment costs not mentioned above.

Operating Costs

1. Direct Labor Cost: The cost of the labor associated with the operation of the robotic work cell.

2. Indirect Labor Cost: This includes any labor cost not covered by the above category. Such items include setup, supervision, and programming.

3. Maintenance Cost: The anticipated cost of maintenance and repair of the robotic work cell. A good "rule of thumb" when data is not available is to approximate the cost to be 10% of the purchase price.

4. Utilities: These costs include the electricity, water, or air required to operate the system. These costs are usually nominal in comparison to the others mentioned.

It is sometimes convenient to represent the operating cost savings by comparing the robotic method against the existing method. This would be easier since it avoids separately listing the operating costs of each of the methods. Material savings, waste reduction, and the advantages of more consistent sample quality are commonly given as justification for savings in this area. One should keep this method in mind when interpreting items one through five of the operating costs listed above.

Economic Analysis

The three most common methods for analyzing economic alternatives are:

1. Payback period method,

2. Equivalent uniform annual cost (EUAC) method, and

3. Return of investment (ROI) method.

In the ideal case, each of these methods should allow the user to reach the same conclusion. However, since each of these methods accomplishes the analysis in a slightly different way, the same conclusion may not always be reached.

Payback Method: This method, as mentioned above, uses the concept of the period of time required for the net accumulated cash flow to equal the initial investment cost. This, of course, assumes that the annual cash flow remains constant from year to year. With this in mind, the following formula may be used:

$$n = \frac{IC}{NACF}$$

where

n = the payback period,

IC = the investment cost, and

NACF = the net annual cash flow.

Since it is unlikely that the net annual cash flow will be constant on a yearly basis, the above equation may be altered to account for the differences in the net annual cash flow from year-to-year.

Here, the subscript i is used to identify each year.

$$0 = -(IC) + \sum_{i=1}^{n} (NACF) \quad .$$

Here, the value of n is determined so that the sum of the annual cash flow is equal to the initial investment cost. The convention most commonly used for this type of analysis is that all costs are treated as negative values, while the net annual cash flow, since it represents revenue, is treated as positive. The second convention is that all cash flow occurs either at the beginning or at the end of the fiscal year. Today, most companies call for a payback period of 1 to 2 years, with 1 year being considered as excellent.

Equivalent Uniform Annual Cost Method: The equivalent uniform annual cost method is used to convert both future and present investments and cash flows into their equivalent uniform cash flow over the expected life of the project. First, the investor selects a minimum attractive rate of return (MARR). This is used as the criteria for decision as to whether the project is a good investment or not. MARR values of 20% to 50% are common for today's engineering economy. Next, the investor uses the MARR to convert each of the investment costs and cash flows to an equivalent uniform annual cost (EUAC). If the sum of the EUAC is greater than zero, then the actual rate of return associated with the investment is greater than the MARR criterion. Therefore, the investment may be considered as attractive. If the sum of the EUAC is less than zero, then the project is considered unattractive.

Return on Investment Method: This method is used to determine the rate of return for the proposed project based on the estimated costs and revenues. This calculated rate of return is then compared with the desired minimum attractive rate of return for the investment. The procedure is similar to that mentioned above, except that the EUAC sum on the left side of the equation is made to equal zero. The value of the interest factor (and the corresponding interest rate) may then be found, which allows the right hand side of the equation to sum to zero.

DESIGN CONSIDERATIONS

It is at this stage of the project that the system designer should try and gather as much information as possible about the job that he or she wishes to automate. This could prove to be a time-consuming process, but it is by far one of the most important. This information will be used to form the basis for establishing both the robotic procedure and the system requirements, as well as the workspace design. The following four primary steps will be used:

1. Establish a robotic procedure,

2. Determine system requirements,

3. Determine robotic requirements, and

4. Develop the workspace design.

Establishing a Robotic Procedure

The designer should begin by defining the overall function of the robotic work cell. This function should then be broken down into the individual tasks that are required to complete the function. These tasks should then be used to make up the experimental method. If the function is currently being performed manually, the designer should observe the tasks being performed by the operator to see if this procedure could be duplicated by a laboratory robot. If this procedure cannot be directly duplicated, then check to see if it can be modified in some way to accommodate laboratory automation. If not, then a new procedure must be developed.

It is useful to develop a chronological table of the events that occur during the processing of each sample. This table may then be used to determine the approximate processing time required for each test. Such information is not only useful in estimating the throughput of the robotic work cell, but may also be used in determining the requirements of any necessary support equipment (such as dispensers or racks).

Determining System Requirements

Now, the system designer should begin to outline the specific details and requirements for the completed system. Specifications for support equipment, error detection, verification, and recovery, as well as data acquisition requirements, should be specified.

Support Equipment

Although support equipment may resemble standard laboratory equipment, it is often modified in some small way to accommodate a robotic environment; for example, a balance may be altered to use remote-controlled doors and interface with a computer to report measurements automatically. A test tube rack may be machined so that the test tubes stand farther apart, allowing the robot to grasp a test tube without disturbing neighboring test tubes. Each opening in the rack may be tapered to help guide each test tube into the center of its rack location.

Occasionally, support equipment is quite unique and sometimes custom designed for a particular application. In the case of sample jars that have threaded caps, a device may be required to cap and uncap a jar as needed.

Dispensing of reagents may also be provided by support apparatus. Here, special equipment is used to handle the measurement and transfer of solids (usually in tablet form), liquids, or gels as required. Next, the samples may undergo some type of mixing operation; methods include wrist shaking, vortex mixing, magnetic stir, or platform shaking. These devices are commercially available and may be adapted for remote computer control.

Error Detection Verification and Recovery

For the efficient operation of the automated work cell, execution of the work cycle is expected to be repeated over and over for the duration of the test. However, malfunctions and errors may occur during the cycle. Some form of correction is then required to restore the automated cycle to normal operation. In some cases, this may require the work cell to be stopped, and human assistance may then be used to correct the situation.

However, there is a trend in both programming and work-cell design to give the robot the capability to sense errors as they occur, and take the appropriate action to restore the system to normal operation. This capability is referred to as error detection verification and recovery. The detection side of the problem is concerned with the use of appropriate sensors to determine when an error has occurred. This would also include the necessary intelligence to interpret the sensory information and categorize the type of error that has occurred.

In general, errors may be classified as random errors, systematic errors, and illegitimate errors. Random errors are those errors that occur as a result of some stochastic phenomena, and are usually characterized by their statistical nature. For example, a slight variation in the size of a test tube might cause the robot to drop that sample. Systematic errors are defined by their frequency of occurrence. They usually result from some bias that exists within the system. An example of this type would be a balance that has not been set to zero prior to its use. The last type of error is the illegitimate error. This is usually the result of some human error. This might occur either in programming the robot or in setting up the workspace; for example, a position may be programmed incorrectly, or a dispensing apparatus may need to be refilled.

The verification process is used to monitor the outcome of the robot's attempt to correct the situation. Here again, the sensors are used to monitor the status of the system to check to see if the problem has been solved and the system is ready to resume normal operation. If the problem has not been corrected, the system must then decide what additional measures should be taken.

The error detection, verification, and recovery system is implemented by means of sensors placed within the work cell together with robotic programming. For highly sophisticated robotic work stations, a large portion of the system programming may be dedicated to this function. For this type of activity, the textural programming languages provide an advantage in programming the sometimes complex control logic that is needed.

The completed system should be capable of monitoring its own operation for unsafe, or potentially unsafe, conditions. This type of detection is called safety or hazard monitoring.

One of the primary methods of handling this type of monitoring is through the use of interlocks. An interlock is a method of preventing the work cycle from continuing unless a certain condition, or set of conditions, are met; for example, the work cycle may be postponed pending a signal from a sensor indicating that the balance door is open and the sample can be removed.

In the design of the work cell, consideration must be given to the regular sequence of events that will occur during normal operation and, also, to those irregular events that may occur during the work cycle. In the case of the regular cycle, the various sequences of activities must be identified, together with the conditions that must be satisfied for successful completion of the task. For the case of potential malfunctions, the system designer must determine a method of identifying the hazard and the necessary actions that are needed to correct the problem. Then, for both cases, interlocks must be provided to insure the required sequence of control during the work cycle. Sensors that may be used for interlock feedback are listed in the following paragraphs.

1. Shear Sensors: This sensor provides the capability to detect slip between the surface of the object and the gripper fingers.

2. Contact Sensors: Contact sensors are useful in recognizing the presence of an object and determining its position with respect to the robot grippers.

3. Photoelectric Sensors: These sensors provide much the same detection as contact sensors, but they do not require the object to come in direct physical contact with the sensor.

4. Force Sensors: Applications for force sensing include holding an object with a specified gripping force, and following contoured surfaces with a specified force level.

Data Acquisition

Based on the type of tasks being automated, the system designer must specify the type of data that is to be collected, and any requirements for handling the data acquisition process. Typically, the data generated by the laboratory work cell is then manipulated using some type of host computer (usually a microcomputer). This computer may or may not handle the programming of the robot controller. In either case, it is the responsibility of the system designer to consider all of the host computer requirements. Such considerations would include the mass storage requirements, onboard memory requirements, the processing speed and relative computing power of the host system, any compatibility requirements that may be necessary for communication with existing equipment, and expendability for future needs.

In terms of the software, it is often useful to consider the programming experience of the system users. This should help the system designer determine how "friendly" the programming and operation of the completed system needs to be. Such options as on-line help menus and tutorials may or may not be necessary, depending on the skills of the operator.

Work Space Design

After the robotic method has been established, it is then necessary to design the robotic work space so as to accommodate each of the required tasks. Because the field of robotics is constantly changing, with improvements being made in both hardware and software, the key

to designing a successful robotics system is flexibility. As technology and laboratory methods improve, flexibility in the work-space design will allow for improvements to be made quickly and efficiently.

The work space is usually designed with the laboratory robot secured in the center of a lab station, or table, with the support equipment surrounding the robot. However, other positions for mounting the robot may be more appropriate; for example, the robot may be mounted overhead allowing for additional space in the work-cell area. Another possibility is that the laboratory robot may be mounted on a track system allowing movement in a plane along the work table. Regardless of the location, laboratory robots require a considerable amount of laboratory space, particularly in multiple robot systems. Therefore, a good robotic design must make efficient use of the available area. This may be accomplished by including common access areas in combined work stations. Another way to increase space efficiency is to think in terms of volume rather than area. By using vertical storage racks and top-loading instrumentation, an increase in the available work space may be achieved.

Determining Robotic Requirements

Determination of robotic requirements depends to a great extent upon the type of application being considered. The system designer should try to carefully study each of the robotic tasks in terms of the parameters mentioned in the Justification Section. This should enable him or her to establish a list of minimum requirements that the robot should be able to meet. It may often become necessary to contact some of the possible vendors of laboratory robotic systems. By doing this, the system designer may gain considerable insight into how and why requirements are specified. Usually the robotic companies have an applications engineer available for this type of assistance. These people are very specialized in their fields and should be able to understand the type of system that the designer hopes to create.

Prioritization: If the application becomes too complicated, it may not be possible to meet all of the system requirements. The two major reasons for this are: (1) the current technology may not be up to par with the system design requirements and (2) the requirements for the application may make the system cost prohibitive. In either case, the designer should prioritize the list of requirements. By doing this, the designer may be able to reach some compromise, both technologically and economically.

Locating Possible Vendors

The next step is to conduct a market study and see what products are available for a particular application. There are a variety of professional journals in which various manufacturers advertise their products. Also, there are market surveys that are published yearly. These surveys list systems by their manufacturer and provide a brief description of their function. The reader should try and accumulate as much information about the manufacturers and their products as possible, and use this information as a means for comparing the various manufacturers' products to see if they meet the system requirements.

EVALUATION OF ROBOTIC SYSTEMS FOR AUTOMATED IMMERSION TESTING OF MATERIALS

The following example is used to help illustrate the procedure for the design and development of a laboratory robotic system as outlined in the Design Considerations Section. This example is based on a problem which has already been successfully automated. The system development and design has been fully documented in a report.[10]

Problem/Goal

The testing and evaluation of complex polymers, as well as other composite materials, is an expensive, time consuming, and, in some cases, hazardous process. A number of technical experts from different areas of interest are required to accurately evaluate a complex organic compound such as an advanced polymer. Since these materials are playing an ever increasing role in the technological advances of today's defense systems, it is of the highest importance that these materials be evaluated by an efficient, reliable testing system.

In the case of fiber-reinforced composite polymers, monitoring the moisture sorption-diffusion behavior can provide useful information on the durability and mechanical properties of the material.[11] One method of investigating sorption-diffusion behavior is by conducting an immersion test. Here, a single specimen is immersed in a test liquid and periodic weight measurements are made to record the change in the sample weight with respect to time.

The manual method, although effective, does prove to have some limitations. The most notable of which is the relatively low throughput. Since the manual method relies on a human operator to take the weight measurements, it is restricted by a 40-hour workweek.

Because the task is monotonous and tedious, it becomes increasingly difficult for the operator to maintain the same testing standards for each sample measurement. Since, in some cases, the percent change in weight is relatively small (less than 2.0%), the test method may become quite operator sensitive; for example, if a sample is not correctly blotted, any residual surface moisture will offset the weight measurement.

In order to provide a more efficient, reliable, and thorough immersion testing system, it has been suggested that a good approach is to use robotics coupled with artificial intelligence to produce an automated test cell. This automated test cell will handle the repetitive, tedious, and operator-sensitive task of immersion testing. The system will also provide the flexibility required to handle different types of specimens and allow for future system expansion.[10] The following paragraph briefly explains the manual procedure for immersion testing of a composite specimen.

Manual Method

Typically, an organic composite test specimen is first conditioned by drying it under a vacuum at 60°C (under the glass transition temperature) until there is no longer a change in weight (approximately 48 hours). Next, the specimen must be allowed to equilibrate in a dessicator before the sample dimensions can be recorded. The sample is then transferred into a sample jar containing 60 to 80 ml of the immersion liquid at a constant temperature.

10. DUNN, S. G. W. *Automated Immersion Testing Robotic System Hardware and Software Design.* U.S. Army Materials Technology Laboratory, MTL TR 89-36, April 1989.

11. DUNN, S. G. W., and HAGNAUER, G. L. *Laboratory Robotics for Immersion Testing of Composite Materials.* Adv. in Laboratory Automation-Robotics, 1986, v. 3, Zymark Corp., Inc., Hopkinton, MA, 1987, p. 273-290.

Weight measurements are then taken at timed intervals until the specimen no longer exhibits a change in weight. In order to maintain as consistent a weight measurement as possible, the sample is removed from the immersion liquid and blotted using highly absorbent filter paper. This is done to remove any surface droplets of the immersion liquid. The specimen is weighed and returned to the sample jar as quickly as possible. For each weight measurement taken, the total immersion time and the specimen weight must be recorded.

Establishing a Robotic Procedure

The overall goal of this project is to design an automated system that will duplicate the manual method of immersion testing as closely as possible. The following sequence of events are listed in chronological order to represent those tasks necessary for carrying out an automated immersion test.

1. The robot selects the appropriate jar containing the immersion liquid and the specimen.

2. Next, the robot uncaps the specimen jar and removes the specimen from the immersion liquid.

3. The specimen must then be blotted between two pieces of filter paper.

4. After the specimen is blotted, the robot must place the specimen in a balance for weighing.

5. The specimen is then removed from the balance and placed back in the sample jar.

6. The jar is capped and returned to the water bath.

7. The time of the weighing and the weight measurement are then recorded by the host computer.

Although this testing procedure is straightforward, the physical operations required are quite complicated. The three primary areas of concern were:

1. Automating the blotting procedure,

2. Manipulating the specimen in and out of the specimen jar reliably and consistently, and

3. Handling the screw cap specimen jars.

Determining System Requirements

Depending upon the specimen's chemical composition, a test may run from several hours to several months. This type of testing will, therefore, require the system to function autonomously with a built-in capability for error detection, verification, and recovery. The necessary support equipment will be required to operate both smoothly and reliably with the rest of the system. Since the system may be running continuously for extended periods of time, accurate data acquisition and its effective handling will also play an important role in the system's success.

Because the immersion specimens may vary in size, shape, thickness, rigidity, and uniformity, a standard specification for sampling was developed. The samples are restricted to rigid 1-inch square, or disk forms, of relative thickness 0.5 mm to 0.6 mm.

An additional requirement is that the robot should be able to handle the specimens directly, simulating the manual testing method as much as possible. Also, the uniform sample size will allow the blotting operation to be greatly simplified for increased reliability.

Immersion liquids used for testing may also vary. A liquid may be hazardous or corrosive, requiring the specimen to be enclosed. For this reason, the samples are placed in a closed screw cap jar with the immersion liquid. The system will be tested using "safe" liquids such as distilled water for the immersion of each sample.

Support Equipment

The need for support equipment has already been addressed to some extent. For this system, peripheral or support equipment will include a dual range, top loading, analytical balance to be used to weigh each specimen. Samples are loaded from the top of the balance by placing the specimen in a custom-designed sample holder mounted to the balance pan. The balance door is to be automatically closed by the robot controller with a relay switch used for verification. The balance should then be interfaced to the robot controller, or host computer, for automatic data acquisition. The balance should be capable of automatically taking a weight measurement and reporting the results to a host computer via an RS232 computer serial interface (or a similar standard of communication).

An automated capping device will be used to rotate the jar, allowing the cap to be threaded and unthreaded, or removed from the jar. Some type of force sensor will be required to determine the extent to which the cap is threaded onto the jar. In addition to capping and uncapping sample jars, the device must also allow the jar to be "oriented" so that the robot can locate and line up on the specimen within the specimen holder.

Various other sensors will be needed to detect and verify possible errors which may occur during the normal operation of the system. Such sensors may include optical or photoelectric sensors for detecting the presence of a specimen or the alignment of a cap for proper threading, and tactile sensors such as contact switches may be used to note the opening of the balance door or closing of the sample blotter.

An automated blotting device is required to dry the sample prior to weighing for an accurate measurement. The blotting device will use highly absorbent filter paper to remove excess immersion liquid from the sample. The filter paper could be mounted on sponges which are closed around the specimen using a computer-controlled solenoid. A hot air gun will then be used to dry the filter paper between samples.

A hot water bath will be used to maintain the immersion temperature of the sample while the study is being conducted (the jars are kept in the water bath between measurements). The rack inside the water bath should handle at least 25 jars and specimens.

Sample holders will be used to support the sample both inside the balance and between blottings, or when the robot is not immediately available.

Error Detection Verification and Recovery

Sensing within the work space, as mentioned before, will play an important role in maintaining the safe operation of the system. Sensors like those mentioned above will be used to assist the robot in "problem situations." After the sensor has reported the information, it then becomes necessary to interpret the data and note the type of error that has occurred. The error would then need to be categorized as either random, systematic, or illegitimate, giving some indication as to the severity. Next, the appropriate action would be taken to either return the system to normal operation or shut down and wait further assistance from the operator.

Data Acquisition

The system will be required to handle, report, and communicate "large" amounts of generated data. As many as 2000 to 3000 weight measurements may be taken during a typical 3-month study. This figure is based on an average of 25 specimens processed continuously over a 3-month period, with an average of one weight measurement per sample per day.

Data acquisition will be handled by the host computer and/or the robot controller. The host computer will be responsible for the overall control of the testing environment. It will handle all storage and manipulation of data, as well as the scheduling of events. The host computer should be able to communicate with the robot controller in order to oversee the testing operation. The robot controller should be able to communicate with both the sensory network and the automated balance. This communication is primarily directed from the sensors and balance to the robot controller for data manipulation and interpretation. The robot controller must then interpret the sensory information and make the appropriate decisions. The measurements are reported to the host computer for recording and data handling.

Work Space Design

The overall testing facility layout is shown in Figure 1. The major system components are as follows:

1. Robot Arm
2. Robot Controller
3. Host Computer
4. Printer
5. Power Supply
6. Balance (with serial computer interface)
7. Capping/Uncapping Device
8. Custom Design Blotting Station
9. Cap Holder

10. Jar Blotter

11. Sample Holder

12. Temperature-Controlled Circulating Water Bath

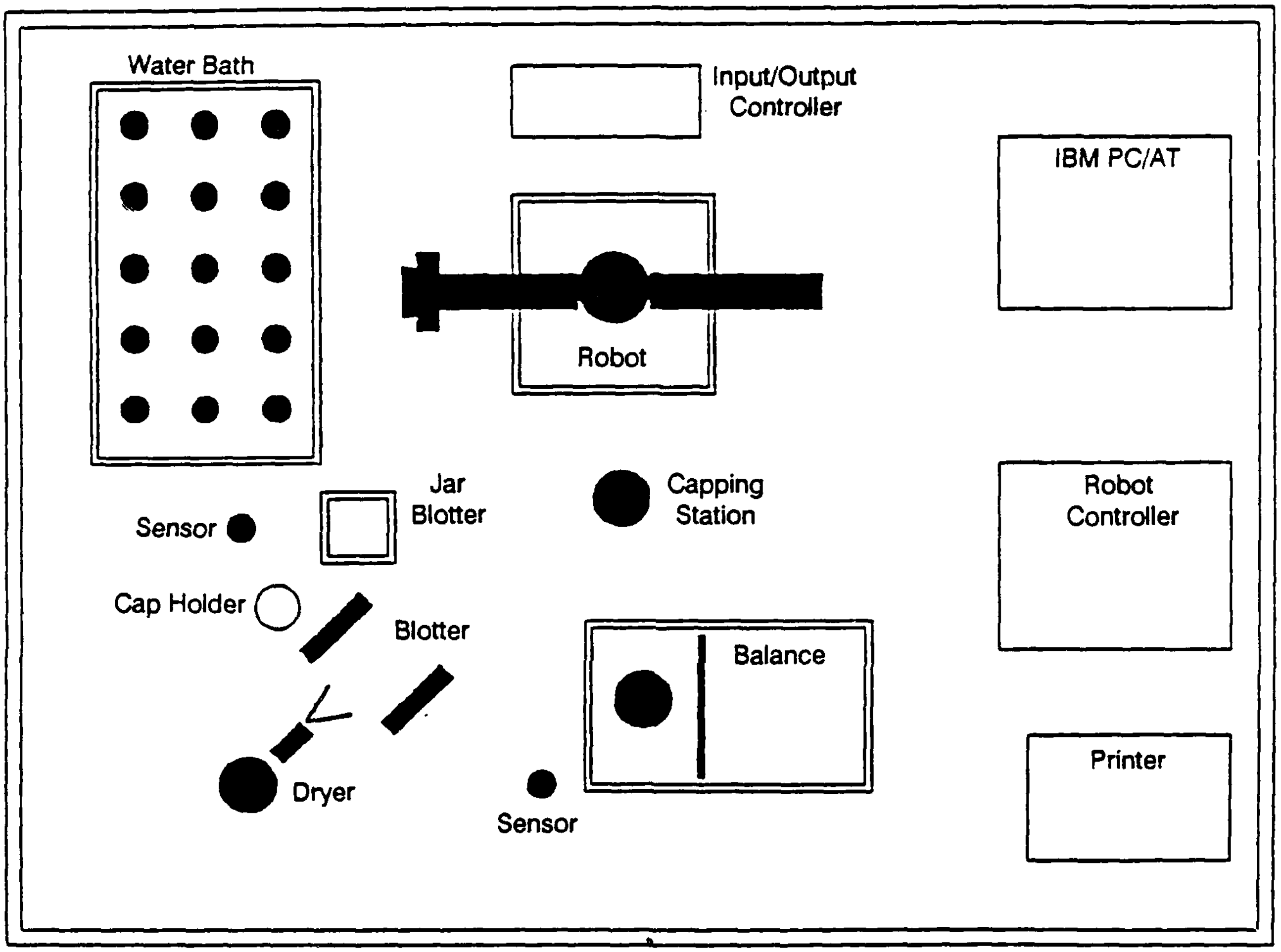

Figure 1.

Robotic Requirements

Since the robotic work space is laid out so as to surround the robot (see Figure 1), each of the robotic tasks will result in various combinations of the following movements:

1. Radial or semi-arch movement,

2. Horizontal or lateral movement, and

3. Perpendicular or vertical movement.

Although these robotic movements could be programmed for either continuous path or point-to-point systems, the simplest methodology would be to use point-to-point coordinates. This would allow the user to define a starting point and a destination for each movement in the task. The tasks could then be stored as subroutines. The main program is then free to call each of these subroutines in any order, as required.

Because the tasks required are made up of the three primary movements mentioned above, the coordinate system most appropriate for this application is the cylindrical system. However, both the spherical and the joint spherical (radial) coordinate systems may be used as well and could offer additional flexibility for future enhancements of the system. Depending upon the robot selected, it should provide at least four degrees of freedom. These degrees of freedom should yield a waist rotation, vertical movement, horizontal movement, and a wrist rotation.

The normal load for this application will be approximately 8.0 ounces or 1/2 pound. To help account for any of the dynamic control problems mentioned in the earlier discussion on speed of response versus stability, the minimum payload requirement will be set to 1.0 pound. This should ensure that under normal operating conditions the robot will be functioning well within its controllable region for maximum performance. Also, this should not present a problem, since most of the currently available laboratory robotic systems are capable of handling payloads of at least 1.0 pound.

To allow for the precise placement of samples in the sample holders, the laboratory robot should have a fairly high precision specification. For this application, the smallest increment of movement or precision should be at least 1.0% of the unit of measure, or 0.01 inch for linear measurement.

The laboratory robot will be required to exhibit a "high" degree of repeatability, at least 3/100 inch. This is further emphasized by the fact that the completed system will operate autonomously both during and after working hours. Without a high degree of repeatability, accumulative positional error would develop as the system operated. This could lead to gross positional errors, which would force the system to shut down. In general, laboratory robots require a high degree of repeatability in order to perform the precision tasks required of them. As a result, this requirement should not be difficult to meet.

The laboratory robot should be relatively easy to program and use. The controller should make use of online, offline, and the teach pendant methods of programming. Each method should support all of the basic programming features mentioned earlier. The robot should be supplied with all of the manuals and the necessary training to operate the completed system.

Available Vendors

A market study was conducted and the following six potential vendors were located. A brief description of their abilities is provided in Table 1. This information is an excerpt from the market survey summary reproduced in the Appendix.

Table 1. A SUMMARY OF AVAILABLE ROBOTIC SYSTEMS

	Co. A Series X	Co. B Series Y	Co. C Series Z	Co. D X-3	Co. E M3	Co. F Z-2
Price ($)	28 - 90,000	36,600	3 - 7,000	4,995	19,900	22,000
Weight	25 - 100 lb	40 lb	30 lb	34 lb	22 lb	38 lb
Footprint	6" x 6"	8.5" Diam.	12" x 12"	6" x 6"	12" x 12"	12" x 12"
Coord. System	Joint Spherical	Spherical	Joint Sphere	Joint Sphere	Joint Sphere	Cylin-drical
Axis 1 Rotation	Full 360°	Min 4° Max 350	Full 360°	Full 360°	300°	376°
Axis 2 Elevation	Full 180°	Min 4° Max 280°	Full 180°	250°	130°	13.4"
Axis 3 Reach	Not Avail.	Min 17" Max 37"	Full 28"	Full 22.5"	Full 25.7"	12.6"
Axis 4 Pitch	Full 180°	Full 210°	Full 180°	Full 270°	±90°	Not Avail.
Axis 5 Yaw	Not Avail.	Not Avail.	Full 180°	250°	130°	Not Avail.
Axis 6 Roll	Full 360°	Full 350°	Full 360°	Infinite	±180°	Full 360°
Precision	0.004"	See Note 2	0.010"	0.01"	±0.1%	0.01"
Repeat-ability	0.002"	0.004"	0.035"	0.04"	0.02"	0.01"
Normal Load Cap.	Based on User Need	5.0 lb	1.0 lb	2.3 lb	2.7 lb	3.0 lb

System Information

Company A: Company A builds the X Series laboratory robot as well as a complete line of sophisticated high technology, electric computer-controlled laboratory robots. Positioning is available through either a point-to-point or a continuous path servo-controlled movement. The working components of the X Series are the robot controller (usually a microcomputer), the robot, and the teach pendant.

Because the X series has been in the marketplace for quite some time now, there are a variety of options and services available to the user; for example, there is a large gripper library for the user to select from, and custom fabrication is available. There are a wide variety of proximity sensors available for the X Series including infrared, laser, and ultrasonic sensors. For tracking sensors, the X Series uses encoders and resolvers to feedback its current location to the host computer. There are also strain gauges and switching sensors available for tactile sensing.

The X Series uses a joint spherical coordinate system with four degrees of freedom. The system is available with an online tutorial to assist the user in operation and programming of the system. The programming language is mnemonic in nature and resembles the English language, making programming easier and more natural to the user. The standard input devices to the system are the host computer keyboard and the teach pendant. However, an additional 32 input channels have been provided for communication with the robotic system. The normal load-carrying capacity for this series is five pounds.

Company B: The next robot under consideration is the Y Series by company B. The Y Series is a point-to-point servo-controlled design which uses a spherical coordinate system. It is important to note that as mentioned earlier, a purely spherical coordinate system is somewhat difficult to program in and requires that most of the coordinate transformations be handled by the host computer.

Host control is provided by a microcomputer with the standard input device being a parallel I/O port. The controller uses the MOS 6502 floating point microprocessor. The standard method for programming is through the use of the teach pendant, and it is possible for multiple programs to be executed simultaneously. Movement is provided by five DC servomotors.

Customer services provided by the manufacturer include custom system design and a selection of grippers including pneumatic, hybrid, electric, and vacuum designs. In the event of a system failure, the average service repair response time is 24 hours.

Company C: The Z Series laboratory robot by company C is the next system to be considered. The Z Series is available in both point-to-point and continuous path models using the joint spherical coordinate system. The robot is servo controlled, and is available with either a two- or three-digit (finger) gripper. The teach pendant and the remote host computer (either a microcomputer or a minicomputer) are the main methods for programming the system. A variety of microprocessor manufacturers are available for use in the controller. Simultaneous execution of multiple programs is possible and online tutoring is available. The programming language is based on Fortran and is primarily English in its command set.

The maximum load-carrying capability is 2.0 pounds. Options are available for tactile and proximity sensing, but tracking is not available. The average up time is an impressive 95%, but hardware service contracts are not available and no estimation for the average service response time was found.

Company D: The X-3 Series by company D is the next system to be considered. Although the original purpose for this robot was academic in nature, it has developed into a fully configurable laboratory robotic system. the primary reason for this is that company D has modeled the X-3 after the high standards of their industrial grade robot. The X-3 System is a point-to-point, servo-controlled system. The coordinate system is based on six joint spherical axes. The axes are driven by independent DC servomotors with optical encoder feedback (tracking sensors). A large library of grippers is available, as well as a host of other accessories. Tactile sensing is provided for through the use of switching sensors and proximity sensing is not yet available.

The host computer is usually a microcomputer. The primary methods for programming are the teach pendant and the remote host computer. The maximum load capability of the system is 2.3 pounds.

Company E: Company E, a company well known for laboratory instrumentation, has developed the M3 Lab System. The M3 laboratory robot is a point-to-point, servo-controlled system with six joint spherical degrees of freedom. The gripper is of a two-digit design and is capable of lifting a 2.7-pound payload. Although proximity sensors are not available, tactile sensing is accomplished through the use of microswitches, while encoders are used for position tracking.

The host computer is a microcomputer which, along with a teach pendant, provides the primary method for programming. Like the company D X-3 System, simultaneous execution of multiple user programs is not possible. However, online tutorials have been provided to simplify programming and operation for the user. The company E robot uses DC servomotors to provide axes movement.

A number of different options are available such as mass storage for user-created software, a liquid dispensing and handling apparatus, racks, weighing accessories, and communications devices. The standard input device for external instrumentation is the RS232 serial port. The system may be enhanced to handle up to 10 different serial ports for data control.

Company F: The last robot for consideration is the Z-2 Laboratory System by company F. The Z-2 System is based on a point-to-point servo-controlled design. A cylindrical coordinate system is used in conjunction with DC servomotors to provide the robot with four degrees of freedom. There are a number of different options available for the user to select from, including mass storage for user-created programs, a large library of grippers, strain and switch tactile sensors, potentiometric tracking, and a variety of proximity sensors. Custom system design is also available for nonstandard applications, or instances where the hardware needs to be either modified or redesigned.

Host control is provided by a microcomputer which, together with the robot controller, provide the possibility for simultaneous execution of multiple user programs. Both teach pendant and remote host computer programming are supported by the system, and online tutorials are available. The programming environment for the Z-2 System is menu driven and the programming language closely resembles English for user convenience and ease of use. The maximum load-carrying capacity for the system is 3.0 pounds.

Force levels on the hand and base axes can be monitored for automatic confirmation without the use of external sensors. An automatic collision detection system built into the base axis will stop and reinitialize the robot when needed. The operator may then correct the problem and continue the program from the point of interruption, or the task may be aborted and rerun at a later time. Two analog-to-digital conversion circuits are built into the wrist. This allows monitoring sensors such as a thermister or a photodiode to be mounted on the wrist for additional data collection. Variable output voltages are available at key locations on the arm for the addition of other control devices.

A corrosive environment package is available for the Z-2 System, allowing the robot to handle corrosive materials, or to be located in a moderately corrosive environment. The cost for the complete system is $3,000, and retrofitting of robots after purchase is not available.

There are two methods currently available for reading bar-coded labels. The first method uses a wand as the reading device, while the second uses a laser to detect and scan bar-coded labels. The approximate cost for both types of scanners is $2,000.

An optional instrumentation interface is available which provides programmable data acquisition from laboratory instrumentation and similar types of control apparatus. Also available is a remote computer interface. The Z-2's capabilities can be greatly enhanced by allowing the system to integrate with other laboratory computers. The remote computer interface provides for bidirectional data transfer and operation of the Z-2 System from a separate personal computer.

The Z-2 controller is capable of handling up to 25 different modules while monitoring the status of the robot. An optional math processor will greatly enhance the average execution speed. The Z-2 controller is made up of a keyboard, monitor, disk drive, and control computer.

Additional Standard Features: In addition to those features mentioned, all of the systems in this report are available with the following standard features:

1. Autoexecution of a user-defined program on system power-up,

2. Diagnostic software for system failure analysis,

3. Power requirements of single-phase 120 volts, 60 Hz., AC,

4. If a voltage regulator is required by the system, it is included at no additional charge,

5. Software updates to the operating system and the programming language are included at no additional charge,

6. The above mentioned software updates are designed to have little or no effect on user-written programs,

7. Problem solving services are available, and

8. Hardware service contracts are available for all systems except for the company D X-3, and company C, Z Series Systems.

Training: Courses are available for training in programming, system operation, and system maintenance by the following manufacturers (at additional cost):

Company A	Company B
Company C (as required)	Company F

Included in the purchase price of the Z-2 System is a three-day training session where a complete understanding of the Z-2 architecture, system operation, system programming for the Z-2 controller, and laboratory stations is acquired. This is followed by onsite training by a systems engineer during the installation and technical assistance phases of the program. An advanced programming school is also available at an additional charge.

Evaluation

Based on all of the available information, the system designer must now select the system he or she intends to use. Depending upon the system requirements and the number of contending systems, the job may be relatively simple or quite tedious. In this case, the selection is fairly straightforward.

The first laboratory robotics system discussed was the X Series system by company A. From Table 1, it can be seen that this system has several advantages and disadvantages in comparison with the other systems. The greatest advantages of this system are its high

specifications for both repeatability and precision, while the most notable disadvantage is its lack of a reach axis (axis 3).

Axis 3 is the reach, or extension, axis which allows the robot to move in a plane parallel to its base. In a cramped laboratory arrangement, such as in this case, it will be very difficult for the robot to work in an area near its base. Since the robot operates in a joint spherical coordinate system, it will have to approach objects near the base from behind. In this configuration, axis 2 (the shoulder and upper arm) is positioned above the item while axis 4 (elbow and forearm) is approaching the object from behind in an effort to get as close to the base as possible and still remain near the bottom of the object for gripping. The situation can be further complicated if there are obstacles to be avoided. However, if the work space is designed properly, this problem can be overcome, or at the very least minimized.

Since this system greatly exceeds the repeatability and precision requirements of the immersion testing system, the extra cost and lack of axis 3 make it difficult to justify for this application.

The next system discussed for this application was the Y Series laboratory robot by company B. This system is also relatively expensive with higher specifications for precision and repeatability. An additional drawback to the Y Series System is that it must be programmed in the spherical coordinate system. As mentioned earlier, this would not be an ideal attribute for this application. Also mentioned in the earlier discussion of this system was the unavailability of tactile and tracking sensors. All of these things combine to demonstrate that the rather excessive cost of this system is difficult to justify for this application.

The next two systems under consideration for this application are the Z Series laboratory robot by company C and the X-3 Series laboratory robot from company D. Although both of these systems are moderately priced, they do not provide a sufficiently high repeatability specification to meet the minimum requirement for this application. An additional drawback to the company D system is that in the event of a malfunction, this system must be returned to the factory for repair. This results in an average time to repair of 2 to 3 weeks. These considerations combine to make these systems less than ideal for this application.

The last two laboratory robots seem to be the systems of choice for this application. Both robots are average in price, and appear to meet all of the robotic requirements. Their capabilities and basic features are quite similar with only minor variations in performance. Since both systems make use of the personal computer as a host controller, they are expandable in terms of both memory and mass storage capability. Both systems offer the RS 232 standard for serial communication. This standard is used quite commonly for peripheral communication and should meet all of the requirements for this application. Their summaries are described in the following paragraphs.

The M3 System by company E is a joint spherical laboratory robot that meets the precision requirement while exceeding the minimum repeatability requirement by 1/100 of an inch. The system is provided with both the pitch axis (axis 4) and the yaw axis (axis 5). Although the additional axes are not required for this application, they might, however, prove useful for future expansion. The M3 System is manufactured with a two-digit end-effector, and additional specialized end-effectors are not available. This could prove to be a limitation if the general purpose end-effector provided cannot handle both the rather large sample jars and the rather small sample specimens.

The last system under consideration is the Z-2 laboratory robot by company F. This system also meets the required precision specification while exceeding the repeatability requirement by 2/100 of an inch (slightly better than the previous contender). The system is designed around the cylindrical coordinate system which was shown earlier to be most appropriate for the immersion testing work-cell design. A large library of end-effectors is available, and custom design work is also available for unique laboratory tasks. The system also provides the capability to automatically change end-effectors if the need should arise. Technical training of the system is included in its purchase price, and other courses and materials are available.

From the above summaries it can be seen that, although both systems could be used for this application, the better choice is the Z-2 Laboratory Robotics System by company F. This system will provide greater repeatability while making use of the cylindrical coordinate system for programming ease. This, together with the ability to automatically change the end-effector, provides increased freedom for system design. Since the difference in cost between the two systems is not substantially different, and training is included in the purchase price of the Z-2 System, the Z-2 System by company F is recommended for the task of immersion testing.

Justification for Automated Immersion Testing System

The last step in the process is to justify using an automated immersion testing system and incorporating the Z-2 laboratory robot.

Increased Productivity

A computer simulation was used to determine what type of productivity enhancements could be expected from the automation of the immersion testing procedure. The simulation was designed to compare the productivity of the manual method versus that of the automated method. The simulation was based on the requirement of having 15 weight measurements taken per sample over a period of 101 days. The following restrictions were placed on the simulation:

Restriction	Manual Method	Automated Method
Time/Wt Measure	2.50 Minutes	6.0 Minutes
Hours/Workday	8.0 Hours	24.0 Hours
Workdays/Week	5.0 Days	7.0 Days
Workweeks/Year	47.0 Weeks	52.0 Weeks
Time to Plot Data	60.0 Min/Specimen	0
Data Base Entry	(0.167 Min) (# of Data Pts.)	0

Note: The workweek for the manual method is based on an average of 2 weeks of holidays, 2 weeks for vacation, and 1 week sick leave per year for the test operator (235 working days).

Based on the above restrictions, the simulation showed that the manual operation will handle up to 266 specimens per year. The automated method will increase the number of specimens processed to 2,775 specimens per year, providing a productivity enhancement in excess of tenfold. This breaks down to an average of 29 weight measurements per day for the manual method, and 237 weight measurements per day for the automated method.

Quality Improvement

By consistently performing a prescribed series of tasks, the robot will demonstrate increases in quality through improvements in accuracy, reliability, and repeatability over the manual method.

Elimination of Undesirable Tasks

Since the task of immersion testing can become monotonous for a human operator when performed over long periods of time, the test method becomes ideally suited for automation. This eliminates the need for a technician to perform what could be considered as an undesirable task, and freeing him or her for more interesting work.

Safety

This issue becomes readily apparent when various other liquids are used as the immersion fluid rather than distilled water. For example, if corrosive, carcinogenic, or other hazardous liquids are needed for testing, then the automation of these tests reduces the possibility of an operator becoming inadvertently exposed to these types of liquids.

Flexibility

As mentioned earlier, by implementing laboratory robotics instead of fixed automation, the user has a greater degree of flexibility in modifying or improving the system as time goes on.

Cost Analysis

It is at this time that the system designer must take a close look at the costs incurred by the project. The goal is to try and compare the existing manual method with the proposed method of automation, pointing out the advantages and benefits of the new system, as well as any disadvantages.

Investment Costs

Laboratory Robotic System

Controller and Basic Robot	$19,000
Teach Pendant Module	$400
System Setup and Installation	$1,200
Computer Interface	$1,500
Total	$22,100

Peripheral Equipment

Balance Computer Interface (RS232)	$1,000
Sample Racks (3)	$450
Capping/Uncapping Device	$2,000
Remote Liquid Dispenser	$250
Power/Event Controller	$1,200
Computer Interface	$1,500
Liquid Distribution Hand	$900
Blank Hand	$500
Balance with RS232 Communications	$6,000
Additional Training and Manuals	$350
Miscellaneous Expenses	$1,250
Total	$15,400

Host Computer System

Personal Computer	$8,000
Graphic Printer	$2,500
Software	$3,500
Total	$14,000

Total Investment Cost $51,500

Economic Analysis: Based on the above-mentioned simulation, the following information was obtained:

	Automated Method	Manual Method
No. Specimens/Yr	2,775	266
Time to Weigh	6.0 min/wt	2.5 min/wt
Data Entry	0.0 min/wt	0.167 min/wt
Time to Plot	0.0 min/spec	60.0 min/spec

Salaries: Based on 235 working days as before.

Grade	Salary/Year	Hourly Rate
GS 09 (Technician)	$30,396	$16.17
GS 11 (Engineer)	$33,169	$17.64
GS 14 (Supervisor)	$48,502	$25.80

Cost Analysis

Manual Method

GS 09 Labor Cost

Cost to Weigh Specimens

(29 wt/day) * (2.5 min/wt) = 72.5 min/day or 1.21 hours
(1.21 hr) * ($16.17/hr) = $19.57/day or $4,597.94 year

Cost to Plot Data

(1.0 hr/spec) * ($16.17/hr) = $16.17/spec
($16.17/spec) * (266 spec/yr) = $4,301.22 year

Cost to Enter Data

(0.167 min/wt) * (29 wt/day) = 4.84 min/day or 0.0807 hr/day
(0.0807 hr/day) * ($16.17/hr) = $1.31/day or $307.85 year

GS 14 Supervisory Cost

(0.4 hr/sample) * (266 samples/yr) = 106.40 hr/yr
(106.40 hr/yr) * ($25.80/hr) = $2,745.12 year

Total Cost Per Year = $11,952.13

Cost Per Specimen = $44.93

Automated Method

Equipment Cost = $51,500

Setup and Programming Cost (based on 480 hours)

(480 hr) * ($17.64/hr) = $8,467.20

System Maintenance (based on two hours per month)

(12 mo.) * (2.0 hr/mo) * ($17.64) = $423.36 year

Total Investment Cost = $59,967.20

Cost Per Year (Maintenance) = $423.36
Cost Per Specimen = ($423.36 yr) / (2,775 spec/yr) = $0.15

Payback Period: Using the payback method of calculation, based on full utilization of the laboratory robotic system (2,775 specimens processed per year), the following results were obtained:

Cost to Process 2,775 Specimens:

Manual Method = ($44.93 per spec) * (2,775 specs) = $124,680.75

Automated Method = ($0.15 per spec) * (2,775 specs) = $416.25

Cost Savings = $124,264.50

Payback Period = (project cost) / (average annual savings)

= [($59,967.20) / ($124,264.50)] * (12 months)

= 5.79 months

Since this payback period is significantly less than one year, this may be considered as a very good investment. The automated immersion testing system should be considered for funding.

Note: This calculation assumes that there is a need for the increase in production to 2,775 specimens/yr. For the manual method to meet this requirement, an additional nine full-time and one part-time technician would need to be hired. This is based on the fact that each technician can handle 266 specimens per year.

COST SUMMARY TABLE

Cost Type	Manual Method	Automated Method
Weigh Sample	$4,597.94	-
Plot Data	$4,301.22	-
Enter Data	$307.85	-
Supervisory	$2,745.12	-
Equipment	-	$51,500.00
Setup and Programming	-	$8,467.20
Maintenance	-	$423.36
Total Cost Per Year	$11,952.13	$423.36
Cost Per Specimen	$44.93	$0.15

APPENDIX. A COMPARISON OF ROBOTIC SYSTEMS FOR USE IN IMMERSION TESTING

	Co. A Series X	Co. B Series Y	Co. C Series Z	Co. D Series X-3	Co. E M3	Co. F Z-2
Warranty	1 Year Parts	1 Year or 2000 Hr	Varies	See Note 1	3 Mo.	1 Year
Price($)	28 - 90000	36600	3 - 7000	4,995	19,900	22,000
Weight	25 - 100 lb	40 lb	30 lb	34 lb	22 lb	38 lb
Footprint	6" x 6"	8.5" Diam.	12" x 12"	6" x 6"	12" x 12"	12" x 12"
Coord. System	Joint Spherical	Spherical	Joint Sphere	Joint Sphere	Joint Sphere	Cylindrical
Axis 1 Rotation	Full 360°	Min 4° Max 350	Full 360	Full 360	300°	376°
Axis 2 Elevation	Full 180°	Min 4° Max 280	Full 180	250°	130°	13.4"
Axis 3 Reach	Not Avail.	Min 17" Max 37"	Full 28"	Full 22.5"	Full 25.7"	12.6"
Axis 4 Pitch	Full 180°	Full 210°	Full 180°	Full 270°	±90	Not Avail.
Axis 5 Yaw	Not Avail.	Not Avail.	Full 180°	250°	130°	Not Avail.
Axis 6 Roll	Full 360°	Full 350°	Full 360°	Infinite	±180	Full 360
Precision	0.004"	See Note 2	0.010"	0.01"	±0.1%	0.01"
Repeat-ability	0.002"	0.004"	0.035"	0.04"	0.02"	0.01"
Velocity Range	Based on User Need	0-55 ips NL 0-30 ips FL	0.117-30 ips	Varies w/Load	0-15.7 ips	Note 5
Effectors Available	Large Library	P,E,V,H	2 Dig. 3 Dig.	Large Library	2 Dig.	Large Library
Tracking Sensors	Encoders Resolvers	None	None	Encoder	Encoder	Pots

	Co. A Series X	Co. B Series Y	Co. C Series Z	Co. D Series X-3	Co. E M3	Co. F Z-2
Tacticle Sensors	Strain Switch	Not Avail.	Options Avail.	Switch	Switch	Strain Switch
Proximity Sensors	IR, Laser, Ultra Snd.	LED	Options Avail.	Not Avail.	Not Avail.	Options Avail.
Normal Load Cap.	Based on User Need	5.0 lb	1.0 lb	2.3 lb	2.7 lb	3.0 lb
Max Load Cap.	Based on User Need	5.0 lb	2.0 lb	2.3 lb	2.7 lb	3.0 lb
Services Avail. to User	Grip Fabri- cation	System Design	System Design	Other Accessories	Other Accessories	System Design
Host Control	Mini Computer	Micro Computer	Mini or Micro	PC	PC	PC
Standard Input Device	32 Channel Various Inputs	Parallel I/O Port	NA	RS232 Serial Port	RS232 Serial Ports	RS232 Serial Port
Min Working Memory	NA	8 K-Bytes	32 K-Bytes	Memory in Controller	256 K-Bytes	Memory in Controller
Memory Expansion	Any Size	32 K-Bytes	128 K-Bytes	640 K (PC)	640 K (PC)	640 K (PC)
Word Length	Depends on Processor	8 Bits	8/16 Bits	8/16 Bits	8/16 Bits	8/16 Bits
Means for Movement	Options Avail.	DC Servo- motors	Options Avail.	DC Servo	DC Servo	DC Servo
Prog. Methods Supported	Teach Pendant & Remote	Teach Pendant	Teach Pendant & Remote	Teach Pendant & Remote	See Comp. D	See Comp. D
Multiple Prog. Exec.	Yes	Yes	Yes	No	No	Yes

	Co. A Series X	Co. B Series Y	Co. C Series Z	Co. D Series X-3	Co. E M3	Co. F Z-2
Prog. Mod. While Exec.	Yes	No	No	No	No	Yes
Recovery From Soft. or Hrdwr. Crash	As Specified by Operating System	Reset System Servo and Restart	Reinitialize System	Reset System	Reset System	Reset System
Results 1) Hrdwr. 2) Soft Crash	Specified Operating System	1) System Disabled 2) System Halts	System Disabled	See Note 6	See Comp. C	See Comp. C
Error Checking	Comp. A Specs	Some	Display Codes	Display Codes	See X-3	See X-3
Online Tutorials	Yes	No	Yes	No	Yes	Yes
Commands English Mnemonic	Both	Info. Not Avail.	English	Both	English	English
Prog. Language	Comp. A	Info. Not Avail.	Fortran	Comp. D	Comp. E	Comp. F
Work Arrangement(s)	Work Surrounds, Work Moves, Robot Move	Work Surrounds Robot	Work Surrounds Robot	Work Surrounds Robot	Work Surrounds Robot	Work Surrounds Robot
Service Response Time	12 Hours	24 Hours	NA	2 to 3 Weeks	No Info. Avail. in 200 mi	24 Hours with°
Spare Parts Stocked	On Site, Local, and Nat'l	Can Be All Usually Nat'l	Nat'l	Nat'l Local	Nat'l Local	Nat'l
Manuals Supplied	Training Program System Maint.	Training Program System Maint.	Training Program System Maint.	Training Program System	Program System	Program System Maint.

	Co. A Series X	Co. B Series Y	Co. C Series Z	Co. D Series X-3	Co. E M3	Co. F Z-2
Training Courses	Program, System, and Maint.	Program, System, and Maint.	As Required	Other Manuals	Not Avail.	See Z-2
Course Location	Nat'l Center User Site	Nat'l Center	Nat'l Center	NA	NA	See A
Cost Per Day for Assist.	$450 at User Site	$350 + Expenses at User Site	$400 at User Site	By Phone No Charge	Both Cost Not Avail.	See Note 7
Collision Control	Not Avail.	Not Avail.	Yes	Not Avail.	Not Avail.	Yes

Abbreviations Used in Table

Mo.	Months
OP Temp.	Operating Temperature (normal)
NA	Not Applicable
ips	Inches Per Second
NL	No Load
FL	Full Load
Pots	Potentiometer Feedback
Strain	Strain Gauges (for tactical pressure measurement)
Switches	Limit Switches (for position detection)
IR	Infra-red Proximity Detection
Ultra Snd.	Ultra Sound Proximity Detection
LED	Light Emitting Diode Proximity Detection
Opts. Avail.	Options Available (such as collision avoidance sensing)
Rec.	Manufacturers Recommendation
Prog.	User-Written Program
Exec.	Execution of User-Defined Code
Int/Sep	Integral Part of System or Separate Unit
Reg.	With Standard Voltage is Regulator Required?
Mod.	User Modification to Program
Hrdwr.	Hardware Crash of System
Soft.	Software Initiated Crash of System
Wrk.	Work is the Necessary Equipment or Material External to the Robot and Required for the Programmed Task
Nat'l	National Distribution Center

End-Effectors (abbreviations):

(P) Pneumatic (E) Electric (V) Vacuum
(H) Hybrid (Dig) Digits or Number of Fingers

Note 1: Company D's warranty is 1 year mechanical and 6 months electrical.

Note 2: The commandable precision for the Y Series System is as follows: joints one and two have 0.00013 radians, and joint 3 has 0.0033".

Note 3: Axis speed for the Z-2 System.

Rotary	10.4 sec/360°
Vertical Up	8.5 sec/34 cm
Vertical Down	5.8 sec/34 cm
Reach	1.8 sec/32 cm
Wrist	4.0 sec/360°

Note 4: Under company D's operating system, a software-initiated interrupt will result in the system being disabled. From this state, normal operation may be continued once the problem has been corrected. A hardware-initiated interrupt results in the need to reset the system in order to continue. As an option, company A's operating system is available for systems using a standard PC as the host controller. Under this system, all interrupts will be handled by the interrupt controller.

Note 5: Technical assistance by company F is available at the user's location at the following rates:

1-5 days	$800 per day
6-15 days	$725 per day
16 or more days	$675 per day

Technical assistance consists of a member of the Systems Engineering Division visiting the user facility to provide applications assistance, training, or programming in the laboratory.

Note 6: All of the systems mentioned here utilize the point-to-point configuration. The Z Series System by company C is the only system mentioned here that does not make use of servo control.

Note 7: Mass storage is available on all of the above systems for program storage.

Note 8: The typical execution speed for each of these systems is one microsecond. In some cases, this value may vary, depending upon the microprocessor used in the robot controller.

Note 9: All of these systems have the capability to automatically begin execution of a robot control program on system power up.

Note 10: Diagnostic software is available with each of these systems, and software updates are included.

Note 11: Each of these systems will support both general material and small parts handling. Collision control and sensing is only available on the company C and F systems.

Note 12: Hardware service contracts are available for all systems except those manufactured by companies C and D. Company D requires that the system is returned to the manufacturer for repair.

Note 13: A problem solving service is made available to all customers by each of the companies mentioned here.

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James D. Kleinmeyer

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This report provides a general overview and outlines a procedure for the design and selection of a laboratory robotic system. The Characteristics and Classification of Robots Section explains the various characteristics and each of the classifications of robot design. The Justification Section deals with the justification for using robotics to automate laboratory procedures. The Design Considerations Section discusses design considerations and system requirements for selecting an automated laboratory robotic system. Finally, the Evaluation of Robotic Systems for Automated Immersion Testing of Materials Section illustrates how selection criteria are utilized to evaluate robotic systems for a particular laboratory application. A detailed example is used to help illustrate the procedure outlined. This example is based on a problem which has already been successfully automated.

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